A WELL CONSTRUCTION PRIMER

(For Pump Installers and beginning Well Drillers)

By Tom Riewe — Jan., 1995

INTRODUCTION

Aquifers

Before explaining the specific aspects of well construction, I would like to describe *aquifers* and how they relate to well construction. In general terms, an *aquifer* is a water producing layer of the earth. In hydrogeologic terms, an *aquifer* is defined as an underground geologic formation—either an unconsolidated formation or bedrock—that is partially or completely saturated with water, into which wells can be constructed to extract economically feasible amounts of water. (To hydrogeologists, the word *aquifer* is pronounced AH-kwa-fur.) (Figure 1.)

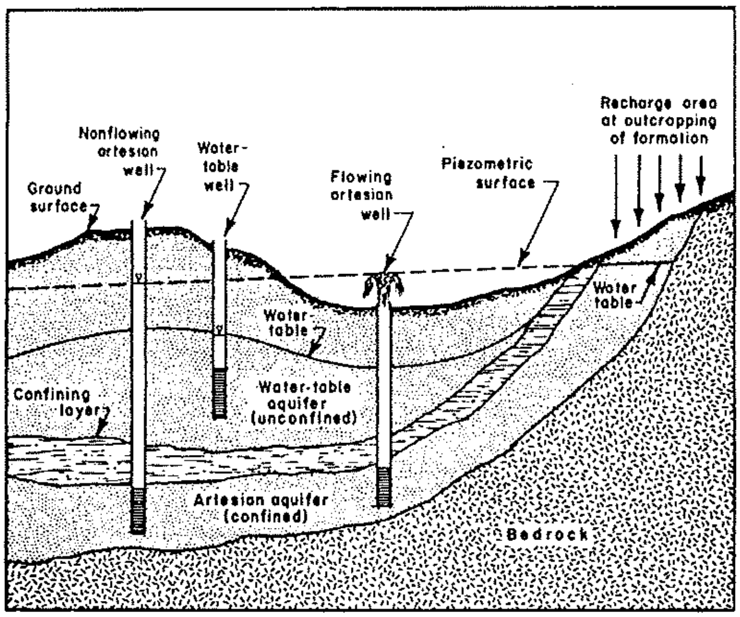


Figure 1. Types of Aquifers (Gibson & Singer, 1971)

You have probably heard people make an analogy of an *aquifer* as an underground river or an underground lake. Neither one of these analogies is a very good one. Yes, there are underground rivers, especially in cavernous *karst* geologic areas like Mammoth Cave, Kentucky. But they are so few and far between that we can consider them to be almost insignificant. Furthermore, if you constructed a well to terminate in an underground river, you would probably not want to drink the water from it. The water has probably not gone through the natural soil filtration processes that would purify it. It would often be bacteriologically and chemically contaminated. An underground lake is also not a very good aquifer analogy because, of course, a lake is open water, whereas an aquifer is *filled* with soil or rock material.

I think an underground *sponge* is not a bad aquifer analogy. It's true that one cannot go underground and squeeze an aquifer like one can a sponge, but in some ways they are similar. Another analogy that isn't bad is a *snow cone*. One can see the colored water moving through the ball of crushed ice similar to the way groundwater moves through a coarse sand aquifer.

Water Witching

Another popular misconception regarding aquifers is a process called *water witching*. You have probably heard about *water-witchers* who go out in the spring of the year and cut a Y-shaped green branch from a willow tree. They walk around on a piece of property with the branch in their hands looking for a suitable place to drill for water. At some point the willow branch *magically* points down to a spot on the ground. That's where the *witcher* tells the well driller to drill the well. And often, of course, that's where the driller finds water!

To me water witching is mostly *malarkey*, but there are some people who swear by it. Homeowners have paid good money to have their property *witched* and, of course, got a good well that produces plenty of water at the spot where their *witcher* has told them to drill. But what the *witcher* hasn't told them is that they could have probably gone to any spot on the property and found water, especially in most areas of Wisconsin. In most humid areas of the world it is possible to find water at just about any location if you drill a well deep enough, because eventually you should encounter an aquifer and the water table.

(Now, wouldn't I be horribly embarrassed if there is actually one-one-hundredth percent of the population that has a sixth *sense* to be able to detect very weak emanations given off by the flow of water in underground fractures within an aquifer, thus making water witching possible! HAH! I'll be *from Missouri* on this one!).

Well Construction

When it comes to well construction, there are two basic things a well driller does when he or she drills a well into an aquifer. He/she either constructs an enlarged hole in the ground, sets well casing pipe in the hole, makes sure the casing is properly sealed within the hole and then sets a screen at the bottom of the casing or drills an open hole below it in bedrock; OR he/she drives the casing from the ground surface; or drives it within and below a starter hole; to a depth necessary to obtain a sufficient yield of water.

These steps are taken not only to ensure that the water pumped from the well is bacteriologically and chemically safe, but also is to ensure that the aquifer is protected. When the casing is properly sealed within the drillhole or is properly driven, it is much less likely to act as a vertical channel that will allow surface water or other pollutants to migrate into the earth to contaminate the groundwater and the aquifer.

WELL CONSTRUCTION TECHNIQUES

WELL LOCATION

The location of a well on a property is just as important, if not more important, than the well construction techniques used to construct it. However, since my topic is well construction, I will emphasize the construction techniques and not go into detail regarding well location aspects. However, suffice to say that it is important to locate a well on the highest point of the property relative to the location of any contamination sources on and nearby the property, and relative to the topographic layout of the lot and its surroundings. If the well cannot be located on the highest point of the property, then it should, at least, not be sited directly down-gradient from a contamination source. Further, minimum separating distances must be maintained between the well and potential sources of contamination such as septic tanks (25'), sewage absorption fields (50'), buried petroleum tanks (100'), animal yards (50'), etc.

WELL CONSTRUCTION METHODS

Throughout the world there are two basic methods for constructing wells; rotary methods and cable-tool (percussion) methods. Rotary methods are newer technology and are a little easier to understand. Mobile rotary drilling machines were developed in the oil drilling industry, where they were used to construct exploration drillholes in the oil fields. They have been used in Wisconsin since about the mid-1950s. Cable-tool (percussion) methods, in their present form, are a bit more rudimentary and have been around much longer, perhaps as long as 100 years or more, but remain in significant use today.

Rotary Methods

It may be easier to understand rotary construction methods by a simple analogy. At one time or another most of us have been to the dentist's office and had little holes drilled in our teeth. A dentist's drill is much like a miniature rotary well drilling rig. It's true, however, that there are some major differences. Rotary well drilling equipment is, of course, much larger than a dentist's drill and must be supported on a large derrick mounted on a large vehicle. (Figure 2.) But both operate on the same basic principle.

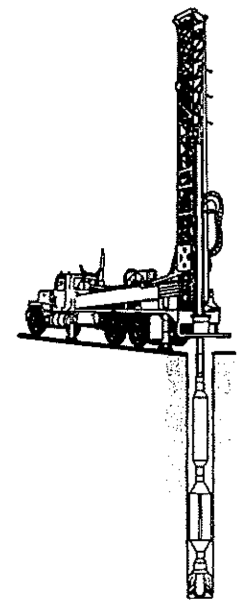


Figure 2. Typical Rotary Drilling Rig

The major difference between the two is that the dentist's drill never penetrates more than about a tenth of an inch or so into your tooth, whereas the rotary drilling machine must penetrate tens and sometimes hundreds or even thousands of feet into the earth. The dentist does not have to worry much about the small pieces of tooth that fly off during the drilling process. He or she can simply remove those from your mouth with a small suction tube. But the well driller must be concerned with the large amounts of drill cuttings that must be removed in order to maintain the drillhole during construction of the well. In order to do this he/she must circulate a drilling fluid that will carry the cuttings up and out of the hole. Three fluids are normally used to remove the cuttings.

Mud Circulation

For constructing drillholes through unconsolidated material (sand, gravel or clay) or soft bedrock, the driller can circulate a sodium bentonite clay slurry through the system. Sodium bentonite is a clay mineral formed naturally from chemically-altered volcanic ash. It is mined mostly in South Dakota and Wyoming. Powdered bentonite is shipped in 50-pound bags. When mixed with water at the drilling site it has the ability to provide a slurry with a *viscosity** high enough to remove the drill cuttings, to keep the drillhole open and to lubricate the drilling bit. Yet, it has a density (weight) low enough to be easily pumpable and not create too great a hydrostatic head (pressure down the hole) to cause the hole to collapse. (**Viscosity* is simply the internal resistance of a fluid to flow. For example, water has a low *viscosity*, molasses has a high *viscosity*).

Bentonite slurry also has a rather unique property called *thixotropy* (thicks-OTT′-truh-pea). *Thixotropy* is the characteristic of some fluids, like new ketchup, that develop a gel structure when not in motion. This gel structure tends to hold the cuttings within the drilling mud slurry when it is not being circulated. This helps prevent the cuttings from sinking to the bottom of the drillhole and reduces the chances of bits getting stuck down the hole.

The powdered drilling mud bentonite is normally mixed with water to make a slurry using a jet-venturi hopper mixing system. (Figure 3.) The mud slurry is pumped through the mixer into a mud tank or a mud pit. It is then pumped out of the mud tank using a mud pump that is usually mounted on the drilling rig. It flows through a hose up to the rotary top drive, down through the hollow drill stem, out through the tri-cone bit, up the annular space between the drillhole and the drill stem and then back into the mud pit. The mud is thus circulated in a completely continuous process. (Figure 4.) The drill cuttings settle out of the mud into the pit and are then removed from the pit by shoveling them out or by other mechanical means.

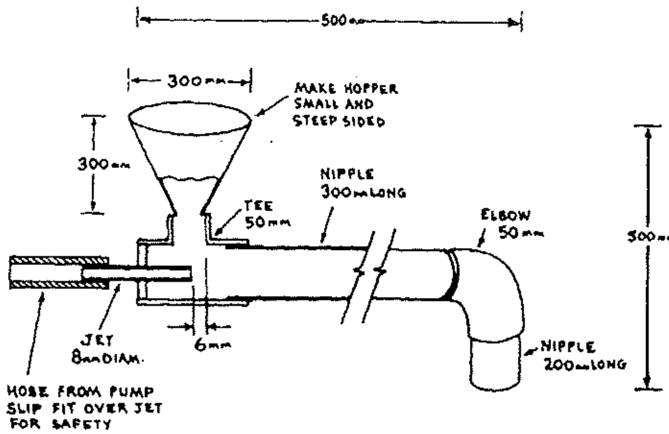


Figure 3. Jet-venturi-hopper bentonite mixing mechanism for rotary drilling mud
(Australian Drilling Manual)

With rotary-mud drilling the geological formation is usually ground up using a tri-cone bit. (Figure 5.) Tri-cone bits were originally developed in the oil well drilling industry. Extremely hard tungsten carbide *teeth* are imbedded into the outside of each of the three cones. These *teeth* grind up the soil and bedrock material. The three cones rotate independently. The entire drill stem and bit also rotate. Many of these drill bits were developed and manufactured by the Hughes Tool Company owned by the late Howard Hughes. This company earned him his first several million dollars and often kept him afloat when some of his other less successful business ventures soured.

Cuttings Removal with Air

When the driller encounters hard bedrock formations, he/she will often switch over from mud to air as the drilling fluid to remove the drill cuttings. When air is used the drilling bit is also often changed. Rather than using a tri-cone bit, the driller will switch to a *down-the-hole hammer* bit. (Figure 6.) The bottom of this bit has a single head and operates in a manner similar to a jack hammer by using compressed air under high pressure. Tungsten carbide *buttons* are embedded into the bottom of the head. The bit vibrates and rapidly separates and returns to the hammer at high frequency and simultaneously rotates. This hammering action chops the formation up into small pieces.

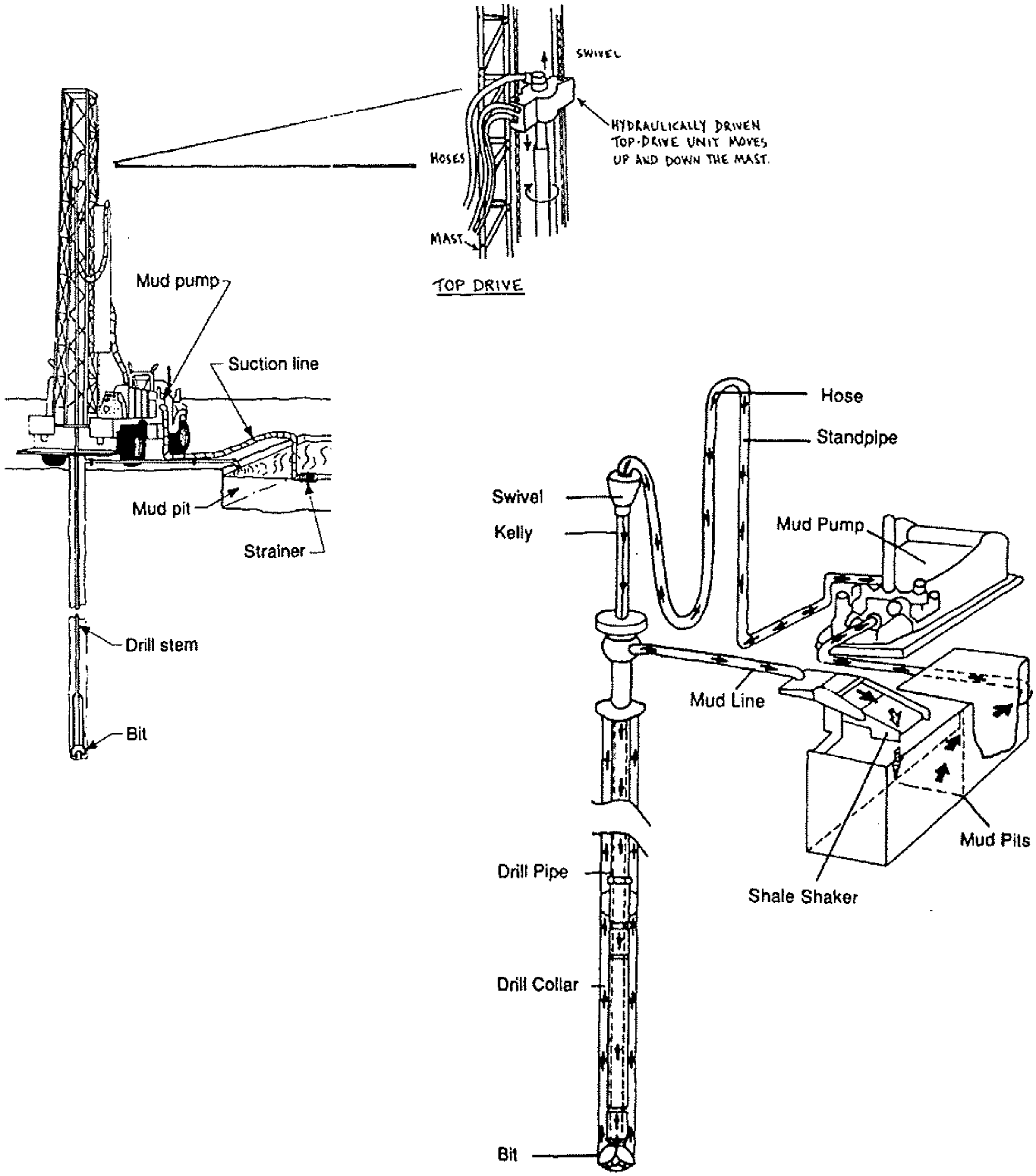
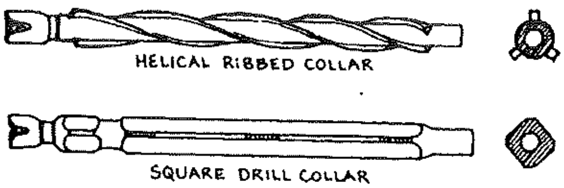
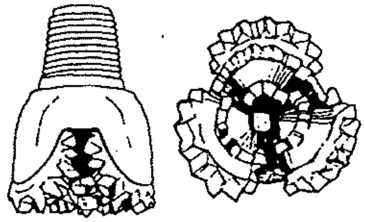


Figure 4. Rotary mud drilling rig and mud circulation components
(Driscoll, 1986; Australian Drilling Manual; Minnesota Water Well Manual)





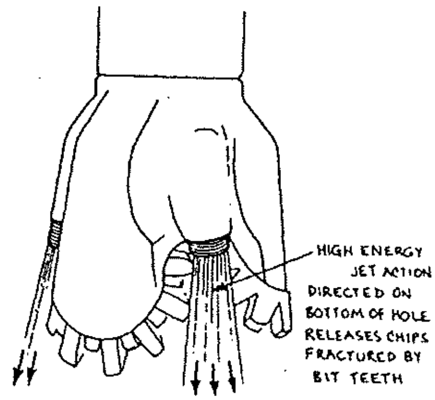


Figure 5. Rotary roller-type tri-cone bits
(Australian Drilling Manual; Gibson & Singer, 1971; Minn. Water Well Manual)

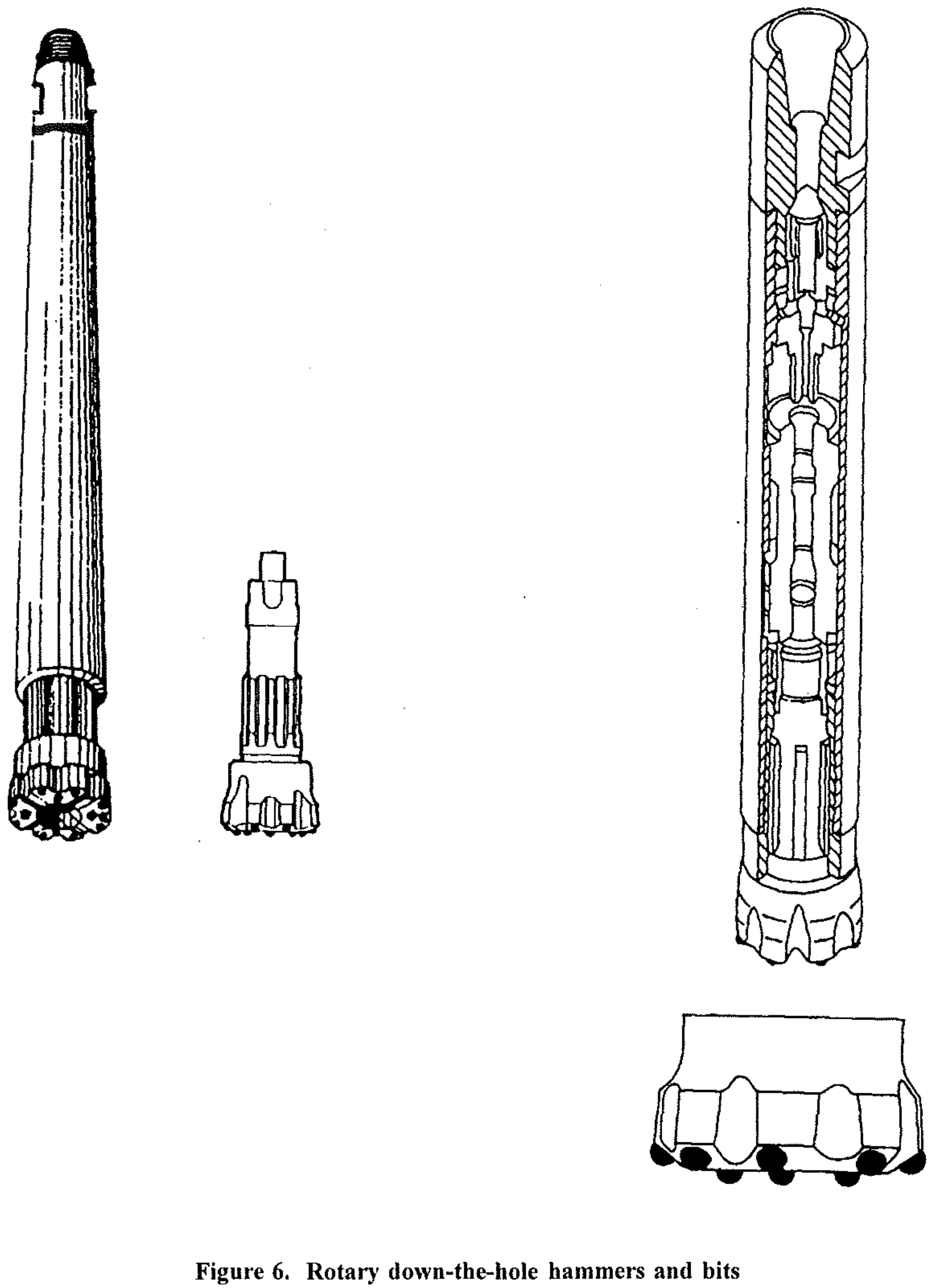


Figure 6. Rotary down-the-hole hammers and bits
(Australian Drilling Manual)

The compressed air blows out of holes in the bottom of the bit and lifts the cuttings between the outside of the drill stem and the inside of the drillhole up to the surface where they fall to the ground. (It's usually not necessary to circulate drilling mud when drilling in bedrock because the drillhole will stand open in the rock.) The air also provides cooling for the bit. Small amounts of water and oil are usually added to the air circulation system for lubrication and protection of the bit. Air can be used as the drilling fluid for constructing bedrock drillholes up to about 8 inches in diameter and to a depth of about 400 or 500 feet.

Air and foam (described below) may only be used in Wisconsin to construct a drillhole when drilling in bedrock, with one exception. If bedrock is encountered at shallow depth and the unconsolidated material above the bedrock is clay or a similar material that will stand open, air and foam may also be used in this material above the bedrock.

Adding Foam to Help Remove Cuttings

For very deep, large diameter drillholes it is often necessary to add drilling foam to the air system to help lift the cuttings up to the surface and keep the drillhole from eroding when circulating high volumes of air under high pressure. Drilling foam is a specifically designed *anionic surfactant*, which is simply a fancy term for a liquid soap. Surfactants are used as an ingredient in many shampoos and dishwashing detergents. Only approved foam products may be used for drilling in Wisconsin.

Rotary Methods - Summary

Rotary drilling methods for well construction can be reviewed as follows:

A drillhole is usually *mudded down* through unconsolidated material to the top of firm bedrock or to a depth within an unconsolidated sand and/or gravel formation where casing pipe and a screen can be set. If bedrock is encountered at great depth, a string of casing pipe is set inside the drillhole and driven to a firm seat in the top of the bedrock. The casing keeps the formation from collapsing and lines-off the upper *vertical zone of contamination.*

The Wisconsin Private Well Code (NR 812) allows the drilling mud and cuttings to remain in the annular space as a seal between the casing pipe and the drillhole for some wells. It is allowed for low capacity unconsolidated formation wells and for bedrock wells when the bedrock is deep and the upper enlarged drillhole does not extend more than 5 feet into the top of bedrock.

If bedrock is encountered at a shallow depth, the enlarged drillhole must be extended into the bedrock, usually constructed with a down-the-hole hammer bit. Neat cement grout must be used to seal the annular space whenever bedrock is encountered above the 40-foot depth (above 30 feet for sandstone) or whenever the upper enlarged drillhole is constructed for any reason to extend more than 5 feet into the top of bedrock encountered at greater depths. Also, neat cement grout must be used anytime the well is a potable high capacity, school or wastewater treatment plant well. For bedrock formation wells an open drillhole is usually constructed below the bottom of the casing into the bedrock using air and/or foam with a down-the-hole hammer bit. Typical wells constructed with rotary methods are diagrammed in Figures 7 to 9.

Rotary methods have, for the most part, replaced cable-tool methods with respect to the number of wells constructed in Wisconsin, but many cable-tool machines are still in operation. Rotary methods are usually much faster than cable-tool methods. However, since the rotary drilling mud circulated in the hole can often plug up the formations, it is possible to pass up layers that can provide enough water for a well.

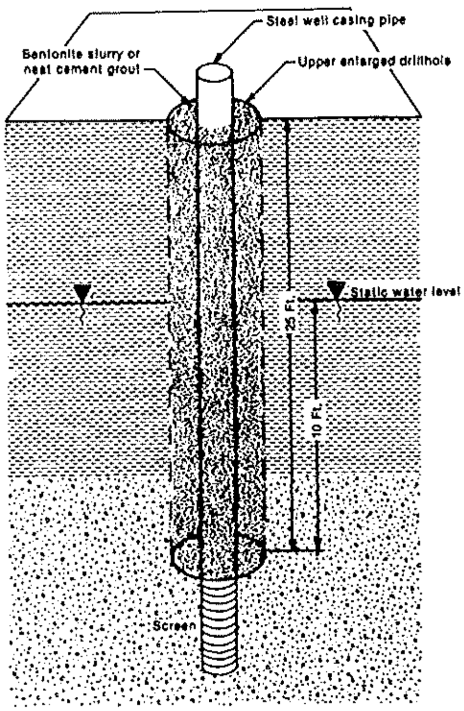


Figure 7. Rotary low capacity drilled well, screened in a sand and gravel aquifer

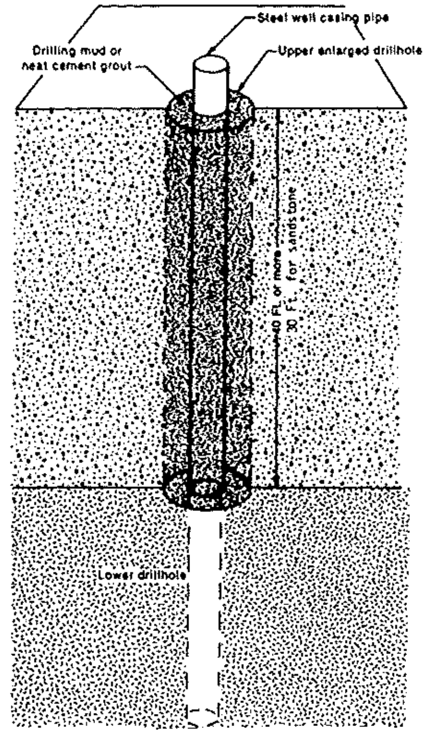


Figure 8. Rotary drilled low capacity well into deep bedrock aquifer

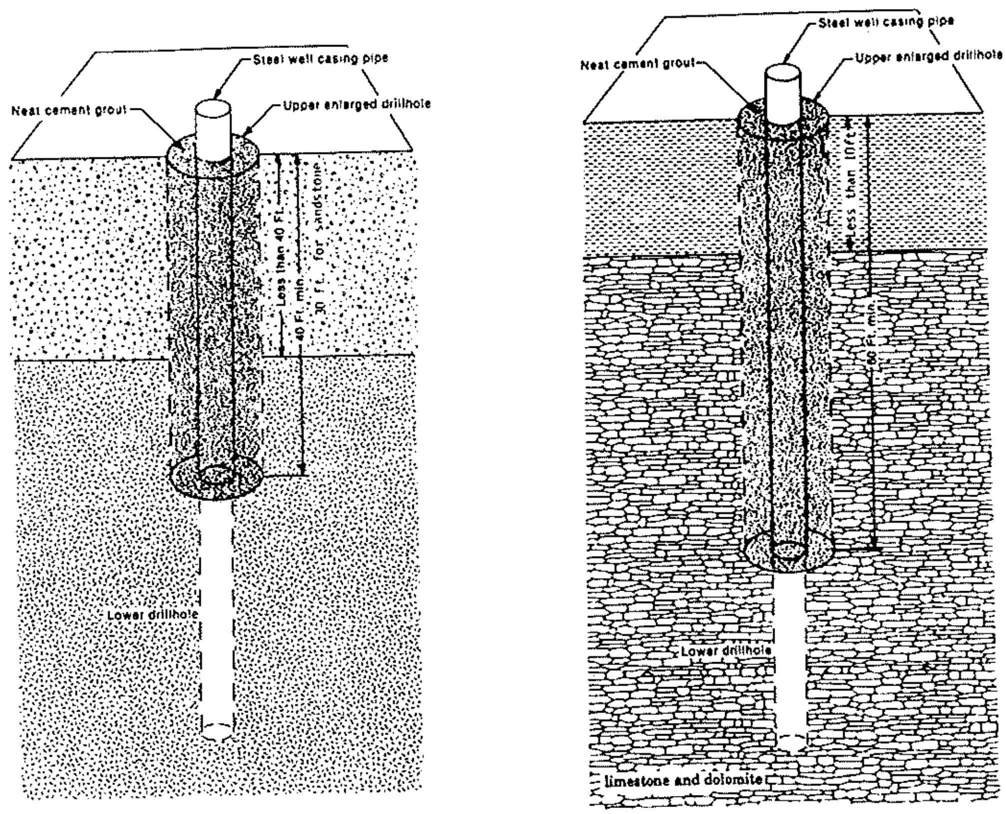


Figure 9. Rotary drilled low capacity wells into shallow bedrock aquifers

Cable-Tool (Percussion) Methods

In areas where there are not large quantities of water in an aquifer or when aquifer layers are thin and interbedded with zones of low permeability, it is sometimes wiser to use cable-tool or other percussion methods to construct a well. Cable-tool rigs are older, smaller and less expensive drilling machines. (Figure 10.) The cable-tool method is in some ways more complicated than the rotary method because it involves a three-part process.

First Part - *Power Chisel*

The first part of the process involves constructing the drillhole with a chisel-type percussion bit. Using the cable-tool machine, the method is similar to a *power chisel*. The long, blunt chisel-type bit is attached to a long string of tools and is dropped from a cable lifted high on a derrick. (Figure 11.) (The cable/pulley mechanism is sometimes called the *bull line*). The bit and stem are repeatedly lifted and dropped into the drillhole to chop up the soil and rock material. In addition, with each stroke the bit rotates a quarter turn. This helps ensure that a straight, round hole is constructed. The drill stem may have an interlocking *jars* mechanism to allow the stem to slide by itself thus preventing damage.

Second Part - *Old Oaken Bucket*

After the drillhole is constructed several feet into the ground, the drill bit is removed from the drillhole and set aside. Then in the second step of the process, the drill cuttings must then be removed from the drillhole. This is done in a manner much like dropping an old oaken bucket down a dug well. However, rather than using a bucket, a *bailer* connected to a cable on a separate pulley system on the derrick is dropped into the hole to pick up the cuttings. (This cable/pulley system is called the *sand line* or, sometimes, the *calf line*). A bailer is a long, hollow tube with a *dart* check valve installed at the bottom. (Figure 12.)

As the bailer is dropped to the bottom of the hole, the *dart* at the bottom of the check valve opens up and allows the water and drill cuttings slurry to rush into the bailer. As the bailer is pulled up out of the drillhole, the dart falls, closing the check valve, thus preventing the slurry from dropping back out the bottom of the bailer. The bailer is then lifted up onto the derrick and dropped off to the side. The dart hits the ground or the bottom of a bucket, the check valve opens and the slurry is dumped onto the ground.

Third Part - *Pile Driver*

The third part of the cable-tool process involves the setting of the well casing pipe. After the drillhole has been constructed 10 to 20 feet into the ground and the cuttings have been removed with the bailer, a string of casing pipe is fitted with a collar-like device called a *drive shoe* made of case-hardened steel. (Figure 13.) It is welded or threaded onto the bottom to assist in the driving of the casing and to prevent the casing from being damaged in the process. The casing is then inserted into the drillhole and driven below it with drive clamps to a depth necessary to obtain water and to line off the *vertical zone of contamination*. (Figure 14.) The drive clamps are bolted onto the top of the drill stem. Lengths of pipe can be either welded together or threaded with couplings. In this third part of the process, the cable-tool drilling machine operates much like a *pile driver*.

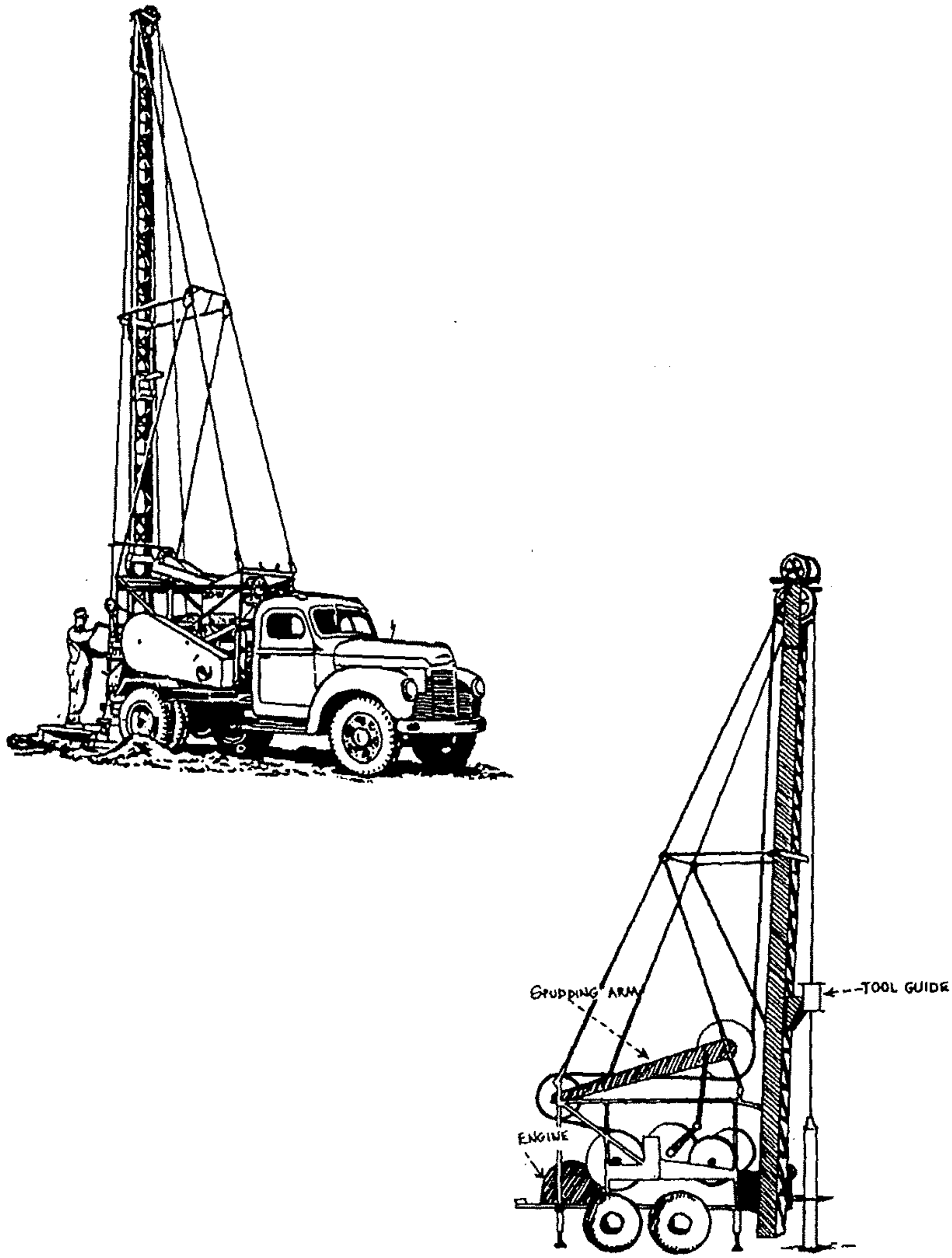


Figure 10. Cable-tool drilling rig and mechanism
(Australian Drilling Manual)

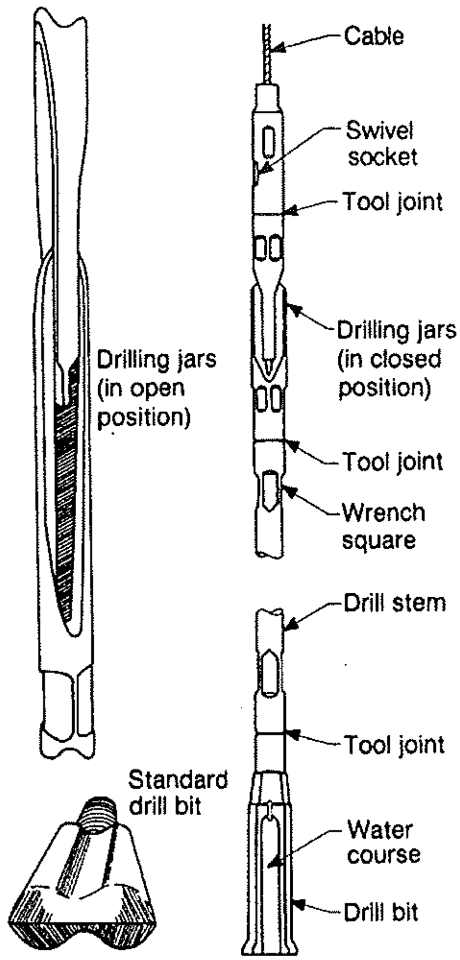


Figure 11. Cable-tool string of tools and bit.
(Driscoll, 1986)

Figure 12. Dart-valve bailer
(Australian Drilling Manual)

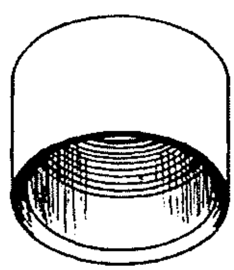


Figure 13. Drive-shoe. Installed on bottom of well casing pipe.
(Australian Drilling Manual)

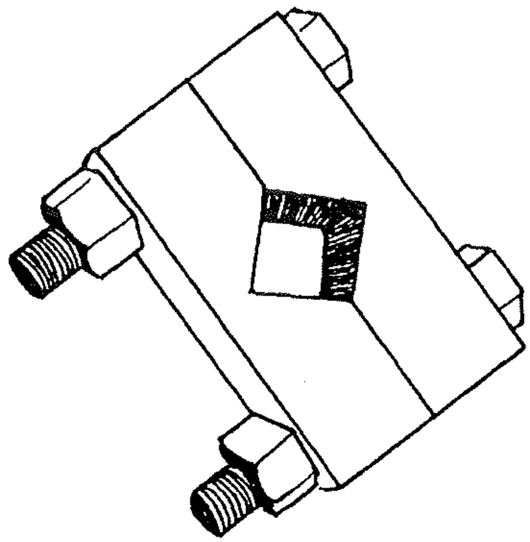


Figure 14a. Cable-tool drive clamp.
(Australian Drilling Manual;
Gibson and Singer, 1971)

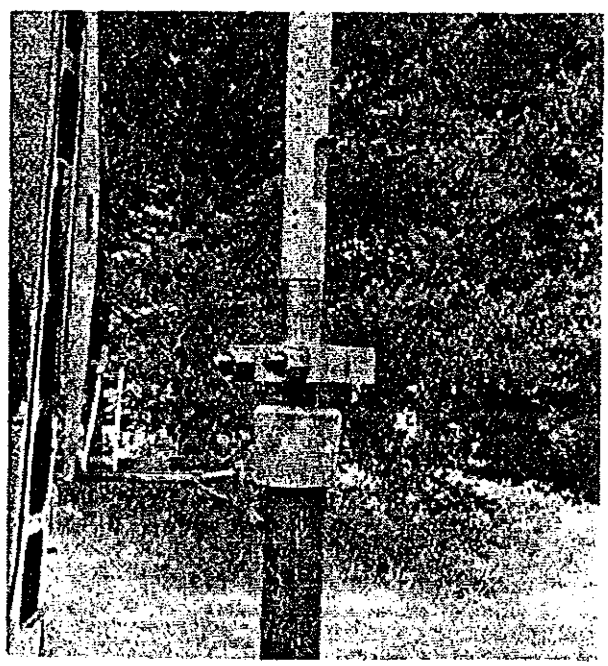


Figure 14b. Driving casing with drive clamps as hammer and drive head as anvil
(Gibson & Singer, 1971)

This three-part cable-tool process is repeated until the well is deep enough to provide an acceptable quantity and quality of water in an unconsolidated formation or until bedrock is encountered. For unconsolidated formation wells the Wisconsin Well Code requires a minimum casing depth setting of 25 feet or 10 feet below the static water level, whichever is greater. If bedrock is encountered at a shallow depth, an upper-enlarged drillhole must be constructed to at least the 40-foot depth (at least the 30-foot depth for sandstone) and the casing must be sealed in place with neat cement grout. If bedrock is encountered below these depths, the casing is driven to a firm seat in the top of the bedrock and a cement grout seal is not required. If limestone or dolomite is encountered above the 10-foot depth, the upper-enlarged drillhole and cement grout must extend to at least the 60-foot depth. In any case an open drillhole is then constructed into the bedrock formation below the bottom of the casing using the chisel-type cable-tool bit.

Cable-Tool Methods - Summary

Cable-tool methods of well construction can be reviewed as follows: The casing pipe can be driven from the ground surface through caving unconsolidated formations. For non-caving formations like clay, an upper-enlarged drillhole, larger in diameter than the casing, must be constructed to accommodate the setting and sealing of the casing. As an alternative to constructing an upper-enlarged drillhole, granular bentonite can be mounded around the top of the casing when the casing is driven through a clay-type formation. (Granular bentonite looks just like cat litter). When an enlarged drillhole is constructed, the casing pipe is set to the bottom of this hole and is then driven to a depth necessary to seal off the *vertical zone of contamination* and to obtain the desired quantity and quality of water. The casing pipe is either driven to the necessary depth in an unconsolidated formation or is driven to the top of a bedrock formation. The well can then be developed with an open bottom casing in a gravel formation, with a screen in a sand formation or with an open drillhole into a bedrock formation. (Typical wells constructed with cable-tool methods are diagrammed in Figures 15 to 17.)

Screen Installation

For unconsolidated formation wells terminating in sand and gravel formations, the well casing pipe is normally either set in a mud-filled upper-enlarged drillhole constructed with rotary methods, or is driven with cable-tool methods to at least a depth where the aquifer will produce the desired amount of water. Once this depth has been reached, the well can be developed in a gravel formation through the open bottom of the casing; or if the formation is sand, a well screen can be installed at the bottom of the casing and sealed with a collar-like fitting called a K-Packer between the top of the screen and the inside bottom of the casing pipe. (Figure 18.)

The screen is installed to hold open the water-producing sand formation and to prevent the well from pumping sand. The Wisconsin Well Code requires a continuous-slot screen, usually made of stainless-steel or PVC (thermoplastic). Continuous-slot screens are quite expensive because they are engineered and manufactured with sophisticated technology to very exacting standards. They are made this way so that a maximum amount of open area is provided to allow as much water as possible to flow with ease into the well and thus produce an efficient well; and to prevent the screen from becoming plugged.

A screen can be set with the *telescoping* (pull-back) method or with the *bail-down*, *wash-down*, or *jet-down* methods. With the *telescoping method* the screen is set to the bottom of the casing and the casing is pulled back to expose the screen. (Figure 19.) In the *bail-down*, *wash-down* and *jet-down* techniques the screen is installed below the bottom of the casing pipe by constructing a drillhole below the bottom of the casing. (Figure 20.) The *bail-down* method involves removing formation material below the casing and the screen and bailing it out of the well, thus allowing the screen to settle into place. The *wash-down* and *jet-down* methods remove aquifer material with a high pressure jet of

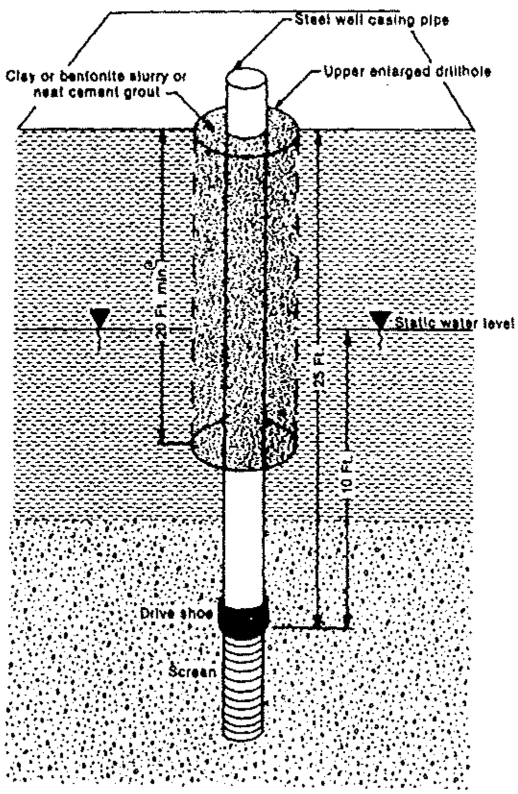


Figure 15. Cable-tool (percussion) low capacity drilled well in sand and gravel aquifer

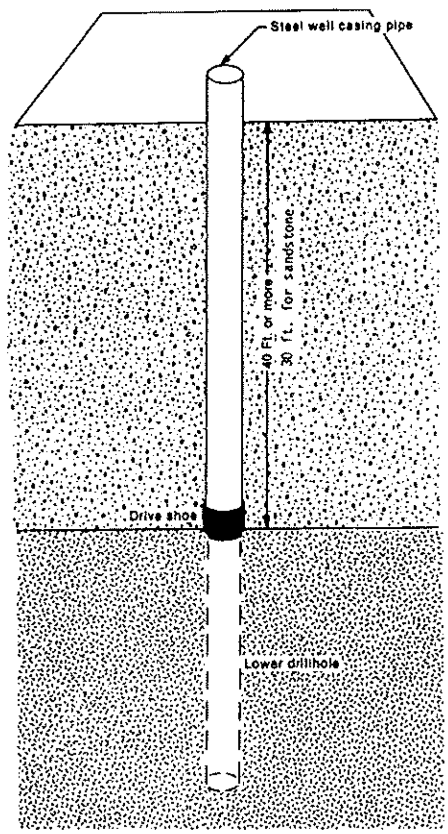


Figure 16. Cable-tool (percussion) drilled well into deep bedrock aquifer with caving material above bedrock

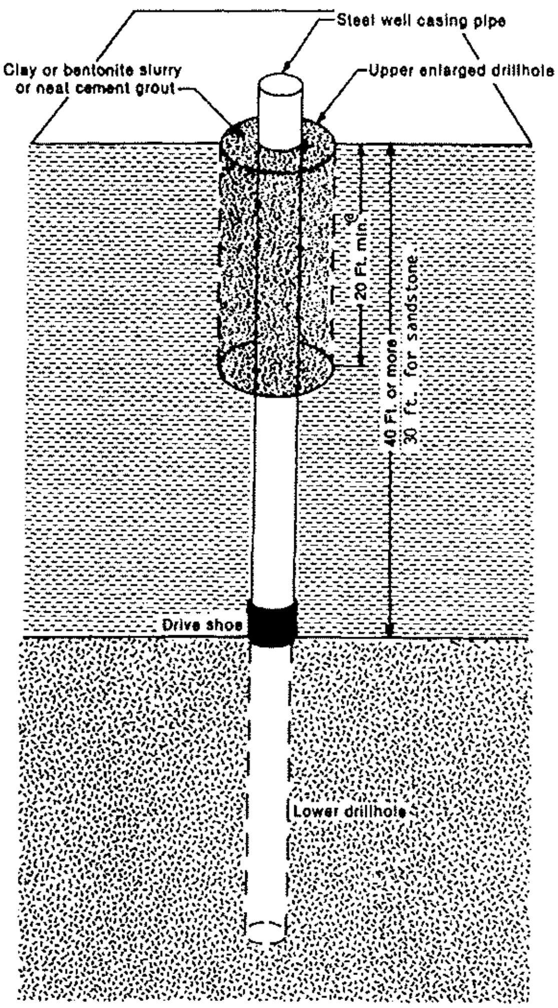


Figure 17. Cable-tool (percussion) low capacity drilled well into deep bedrock with non-caving material above bedrock

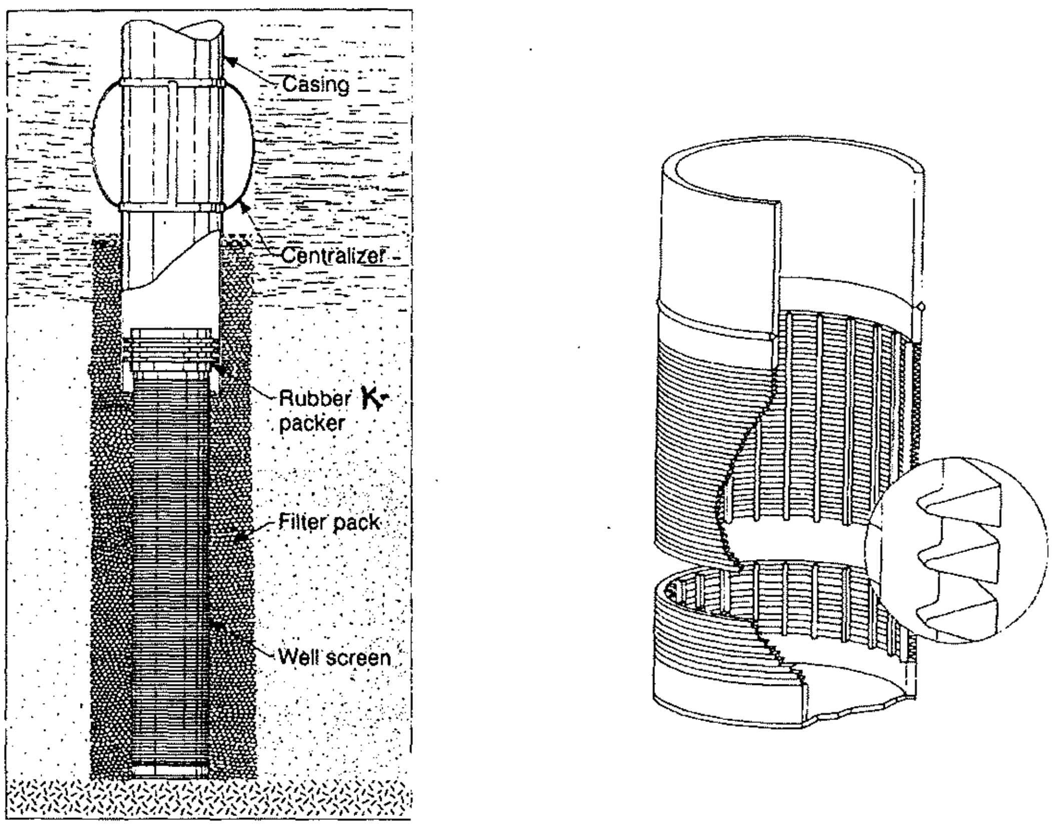


Figure 18. Continuous-slot well screen
(After Driscoll, 1986; Johnson Screen)

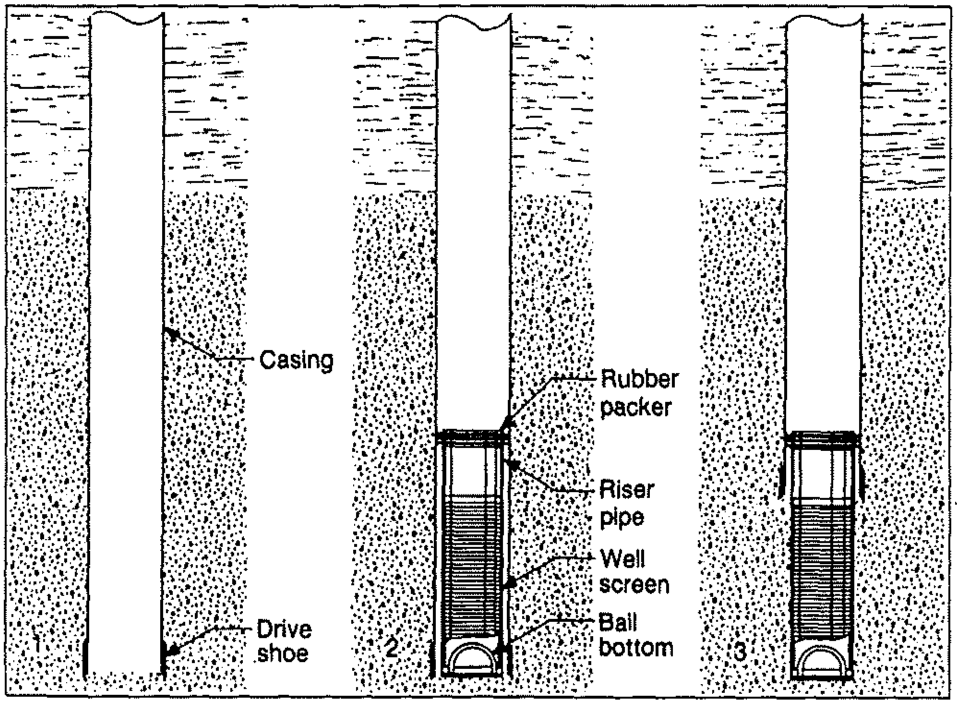
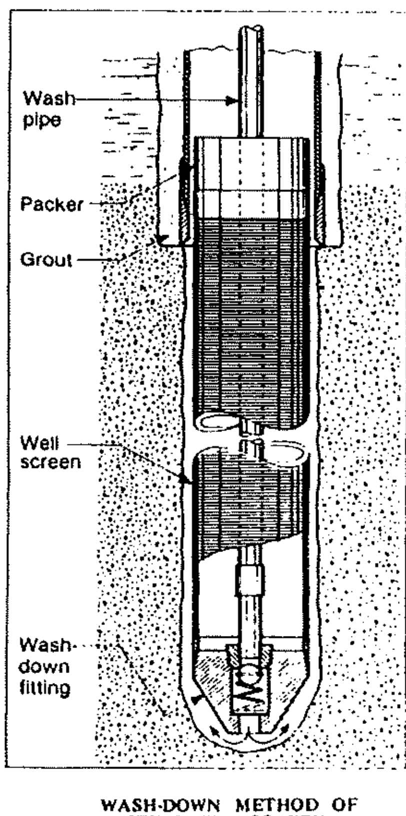
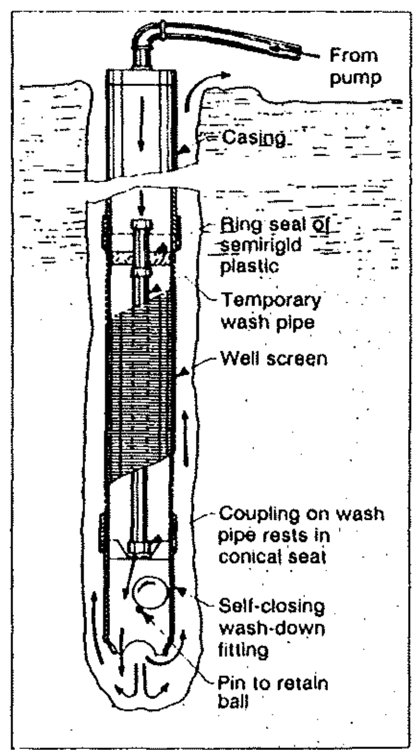


Figure 19. Telescoping (pull-back) method of screen installation
(Driscoll, 1986)

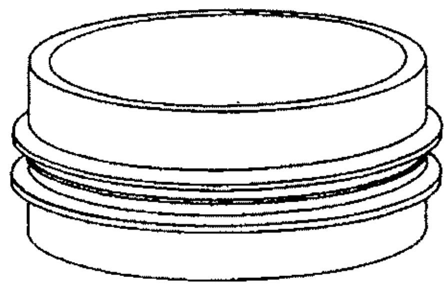


WASH-DOWN METHOD OF SETTING WELL SCREEN.



JETTING WELL SCREEN INTO POSITION.

Figure 20. Wash-down and jet-down methods of well screen installation
(Gibson and Singer, 1971)



Flexible neoprene ring mounted to steel or stainless steel body provides sand-tight seal against inside of casing.

Figure 21. K-packer seal for well screen
(Johnson Screen)

water and allow the screen to settle down into place below the casing. A rubber-like neoprene *K-Packer* collar is placed around the top of the screen to provide a seal between the top of the screen and the bottom of the casing pipe to prevent sand from entering the well. (Figure 21.)

Well Development

For screened and open-bottom cased wells in unconsolidated sand and/or gravel formations, well development is as important and perhaps even more important than the actual construction of the well. (Well development may also be necessary for some fractured bedrock wells when the fractures within the aquifer are filled with sediment). Well development is the process of removing the fine sediment particles and drilling mud residue from the aquifer formation surrounding the screen or the bottom of the casing.

All well drilling methods damage the aquifer formation thus reducing its ability to transmit water towards the well. Rotary mud-circulation methods usually plug the formation with drilling mud. In the process of driving the casing, percussion methods usually compact the formation and clog it up.

When done properly, well development will reassemble the formation particles closely surrounding the well so they become graded from larger to smaller sizes in a direction moving away from the screen. This creates a natural filter surrounding the screen and allows water to flow towards and into the screen with greater ease. Further, it prevents sand from entering the screen. Sand can be a nuisance and will usually reduce the life of the pump. Regrading of the formation particles also helps maximize the yield of water from the well and makes both the well and the pump more efficient, thus reducing both the amount of energy used and the cost to operate the pump.

There are several methods used for well development. The easiest method is to simply pump the well at a rate significantly higher than the rate of the pump to be permanently installed in the well. This is referred to *overpumping.* Overpumping is usually not very effective however because it only causes water to move in one direction through the screen. This allows fine sediment to bridge and get trapped just outside the screen.

The most effective development methods force water both in and out of the screen—and the surrounding formation—at high velocity. (Figure 21a.) Movement of water in and out keeps the formation sediment moving and allows the fine particles to find their way into the well where they can be removed. This is called *surging.* The easiest way to surge the well is to alternately pump the well and allow the pumped water to fall back into the well. This can be done with a submersible test pump or by *airlift pumping. Air-lift pumping* is done by injecting compressed air from the drilling rig compressor down a small diameter tube inserted down to the bottom of the well.

Surging with a *surge block* is an even more effective technique. This is accomplished by inserting a piston-like *surge block* into the well and moving it up and down within the casing like a plunger to move water in and out of the screen with force. (Figure 21b.) This can also be done by raising and lowering a bailer in the well using a cable-tool machine, but this is not as effective.

Perhaps the most effective method of development is *jetting.* A *jetting tool* is placed down inside the screen and high velocity streams of water are injected horizontally out this tool, through the screen, and into the surrounding formation. (Figure 21c.) The jetting tool is rotated and moved up and down within the screen in order to get more complete agitation and rearrangement of the formation particles outside the screen. Jetting is most effective if it is done simultaneously with *air-lift* pumping. This is because the fine sediment that enters the screen is immediately removed up and out of the well and therefore cannot be forced back out the screen into the formation or fall to the bottom of the well.

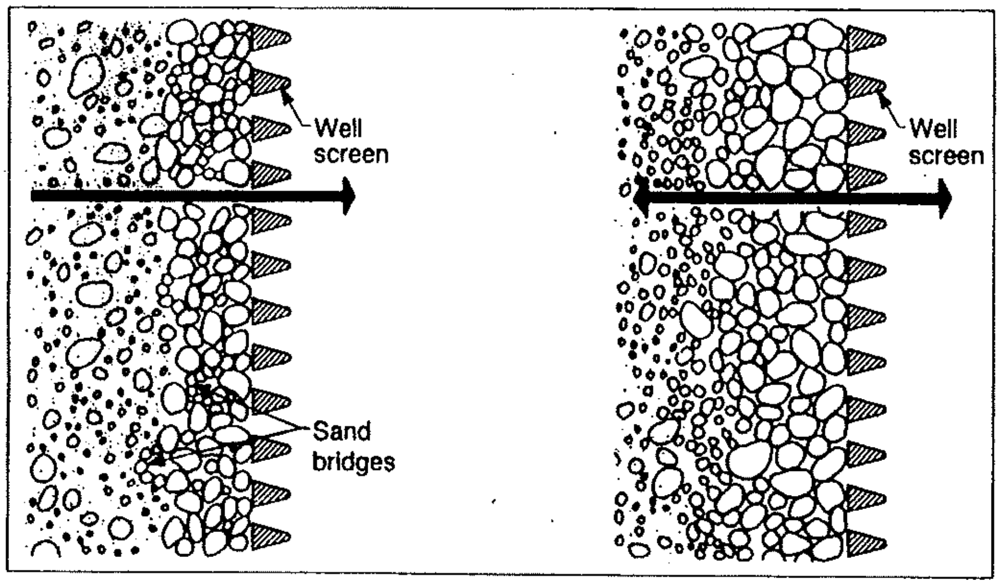


Figure 21a. Well development is most effective when the process moves water both in and out of the screen vigorously—as on the right side of this diagram. (Driscoll, 1986)

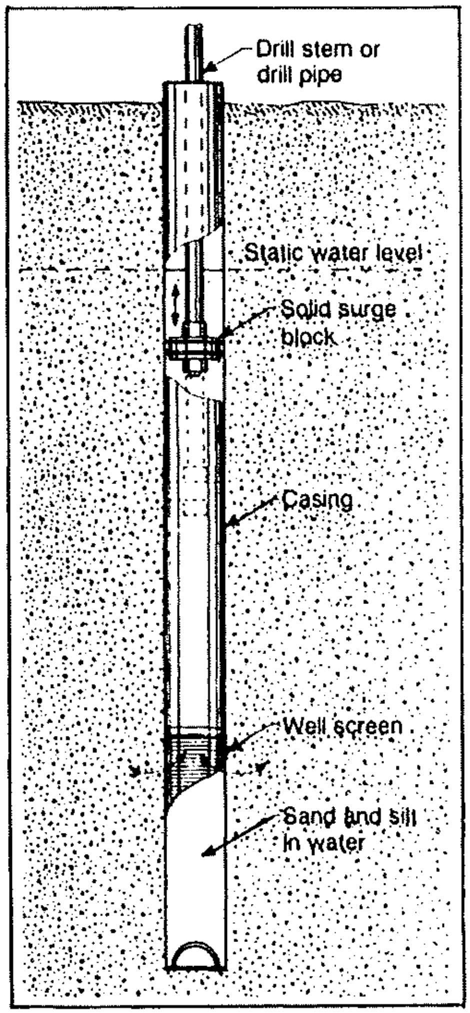


Figure 21b. Well development by surging the well with a surge block
(Driscoll, 1986)

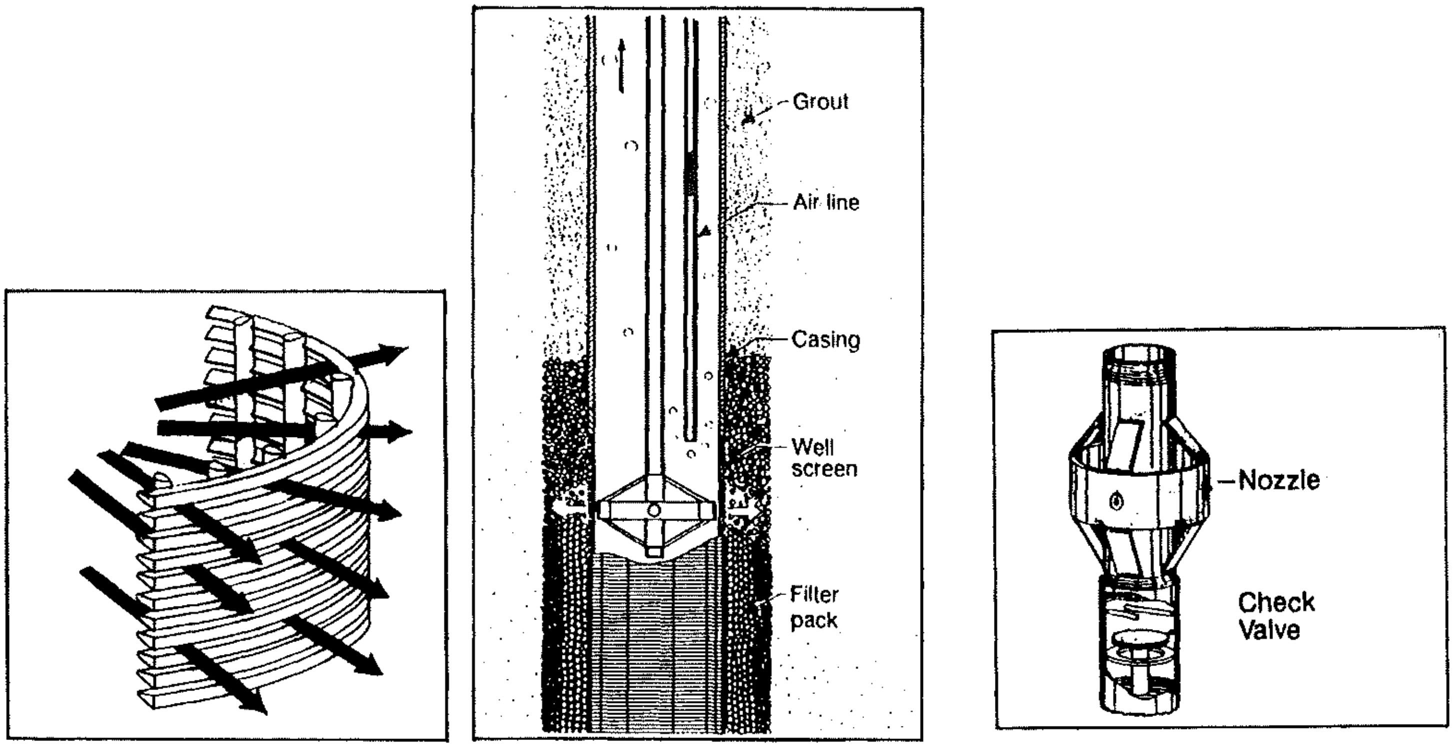


Figure 21c. Well development using jetting in conjunction with air lift-pumping.
(Driscoll, 1986)

Care must be taken when using development methods, especially surging and jetting. If they are done too vigorously at the beginning of the process when the formation is still quite plugged, significant differential forces can be applied on the screen. The development process must started slowly and gently and then increased in intensity very gradually. If care is not taken, the screen can be damaged or can even collapse.

Other development methods are used to try to increase the yield of water from low-producing crystalline bedrock wells such as the "granite" wells in northern Wisconsin. For many years the most common technique used was *blasting*. Dynamite was placed down into the open bedrock drillhole, the well was filled with water and/or sand, and the dynamite was detonated. (Figure 21d.) This method had mixed results. A newer technique called *hydrofracturing* is in wider use today and usually produces better results. It is described in detail at the end of this document.

Casing Hammer (Combination Rotary-Percussion) Method

There is relatively new equipment for constructing wells that uses a combination of rotary and percussion methods that allows the driller to construct the drillhole and drive the casing in the same process. The mechanism is called a *casing hammer* and is usually mounted on the derrick of a standard rotary-type drilling rig. Rotary bits are inserted inside to drill below the casing and the casing is also driven, so the process is both a rotary and percussion method. A tri-cone bit or a down-the-hole hammer bit can be used. The drill cuttings are removed with compressed air during the drilling and driving, so the process is very fast and efficient. (Figure 22.)

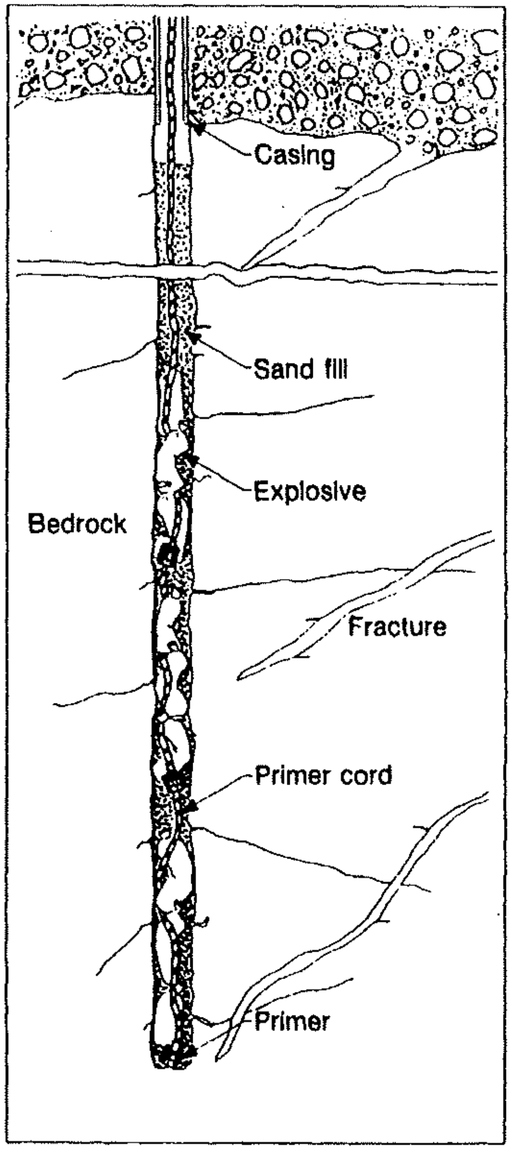


Figure 21d. Well development of a fractured crystalline bedrock well by blasting with dynamite.
(Driscoll, 1986)

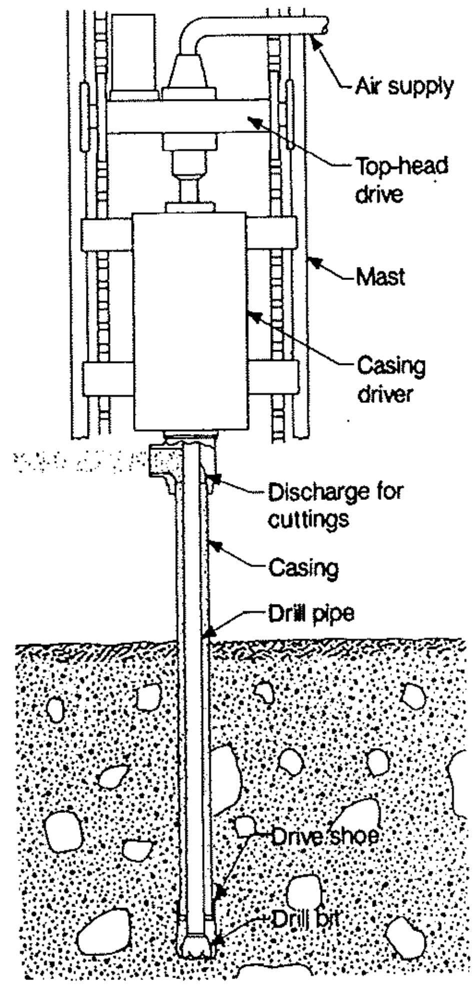


Figure 22. Rotary, casing-hammer drilling configuration
(Driscoll, 1986)

Dual Rotary (*Barber* Drilling Rigs)

An even newer concept of rotary drilling was conceived in the late 1970's in Canada when *Barber* rigs were developed. This drilling system called "Dual-Rotary" is similar to the casing hammer, but instead of the casing being driven, it is advanced into the earth by turning it with a second rotary drive unit mounted on the rig derrick. A standard rotary top head unit turns the drill stem and bit inside and below the bottom of the casing pipe in the same manner as a casing hammer rig. However, the second rotary drive unit—mounted on the derrick below the top head unit—grips onto the casing with powerful *jaws* and turns it into the ground. Pipe sizes up to 24 inches in diameter can be easily handled. A ring, having tungsten-carbide *buttons* imbedded into it, is welded onto the bottom of the casing to act as the casing bit. Both the top head unit and the lower casing unit are independently raised and lowered on the derrick by hydraulic cylinders. These units do not use chains, sprockets, cables, belts or clutches as do other rotary rigs, so maintenance problems are fewer.

As with the casing hammer system, a very large air compressor provides air to blow the drill cuttings up between the casing and the drill stem. The top head unit can also be hydraulically tilted to make it easier, more efficient and safer to handle drill rod and casing pipe. This drill system works especially well in drilling through overburden composed of large gravel, cobbles and boulders. The biggest disadvantage of these rigs is that they are very large and very expensive.

Jetting Methods

Jetting is normally done for small diameter (usually 2-inch) residential and cottage wells. This method uses water under high pressure forced down at high velocity through a hollow tube out the bottom of a bit. The water breaks up the formation and washes the cuttings up to the ground surface. The bit is raised and lowered periodically and the drill stem rotated so that a straight, round drillhole is constructed. As with rotary-mud drilling, the water used for jetting is circulated in a continuous system. When the water and drill cuttings reach the surface they are allowed to flow into a pit or tank where the cuttings fall out and the water is recirculated. (Figure 23.)

After the drillhole is extended to a given depth, the drill stem is removed. A string of casing pipe—installed with a drive-shoe on the bottom—is then inserted into the hole and driven in a manner similar to the cable-tool method into the formation.

Driven-Point (Sand-Point) Wells

There is another very simple method of constructing a well that can be done by hand without the use of a drilling machine. Such a well is a driven-point (sand-point) well. These wells can often provide enough water to supply a single-family residence or a cottage. They are actually not drilled wells, but are very practical for shallow sand and gravel aquifers having high water tables.

Driven-point wells are constructed by attaching a drive-point screen to the bottom of a small diameter galvanized pipe (usually 1¼-inch or 2-inch diameter); and then by driving the point and pipe into the ground to a depth necessary to intercept an aquifer and obtain the desired quality and quantity of water. The casing depth setting requirements for driven-point wells are the same as those for drilled unconsolidated formation wells. (See depth of casing requirement section below.) This type of well construction is similar to simply driving a spear into the ground. It can be accomplished by one person working alone. The person can drive the sand-point screen and pipe into the ground with a fence post driver or with a tripod, pulley and weight arrangement. (Figure 24.)

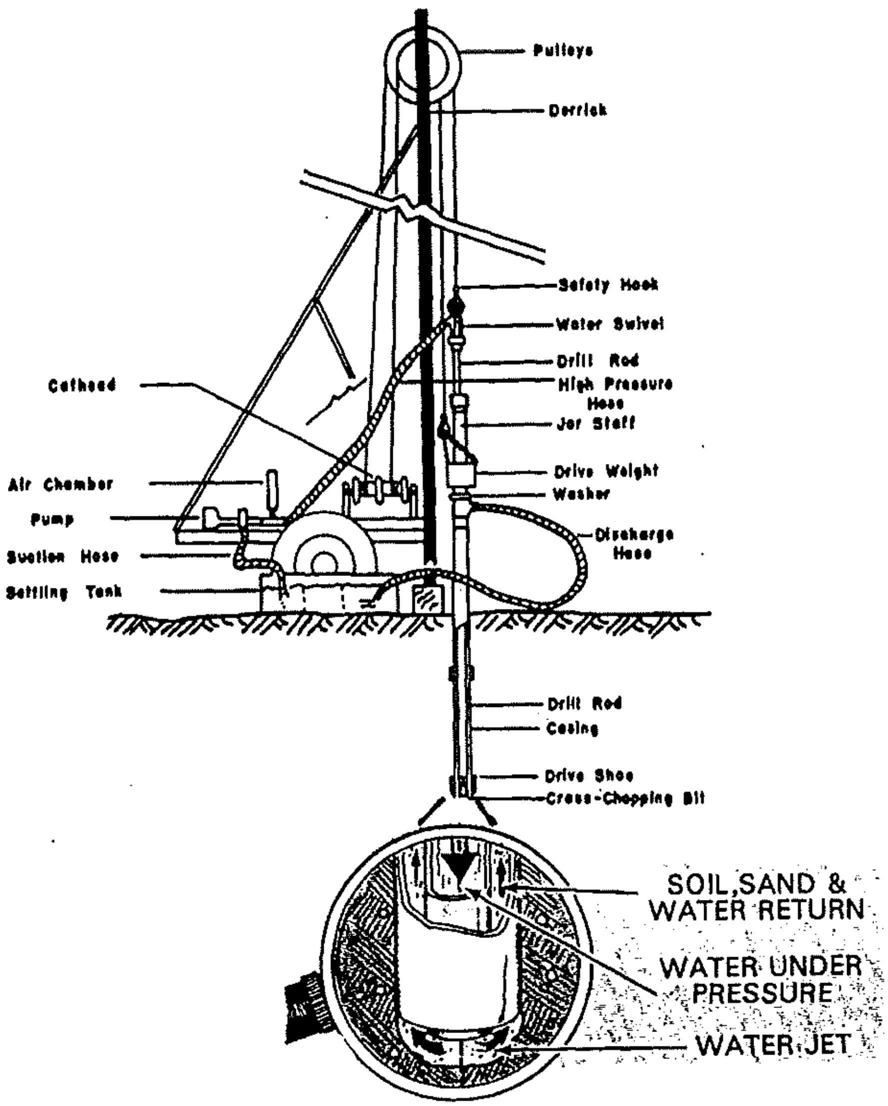
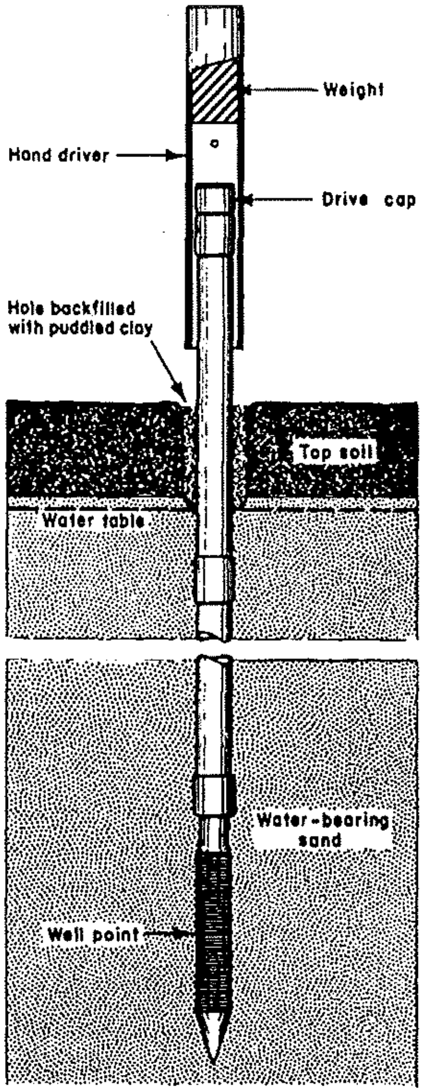
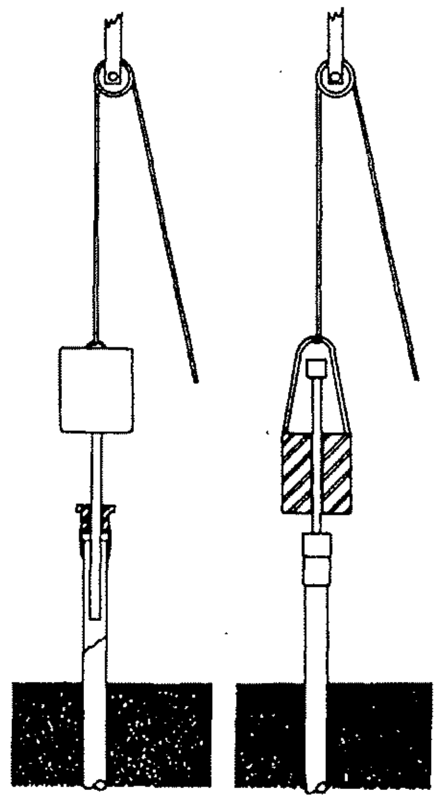


Figure 23. Jetting drilling machine configuration
(Minnesota Water Well Manual After Matlock, 1970)



HAND ASSEMBLY



DRIVE-BLOCK ASSEMBLIES FOR DRIVING WELL POINTS.

Figure 24. Methods of installing driven-point (sand-point) wells (Johnson Div. UOP.-1972; Gibson and Singer, 1971)

DEPTH OF CASING REQUIREMENTS

It is very important to construct a well with the necessary depth of casing pipe to line off the *vertical zone of contamination* and to protect the aquifer from contamination. This will help ensure that the well will produce bacteriologically and chemically safe water. In Wisconsin, the criteria for casing pipe depth setting is based on whether the well is a sand and gravel formation well or a bedrock well.

For unconsolidated formation wells, the minimum depth of casing is 25 feet or 10 feet below the static water level, whichever is greater. This means that if the static water level is, for example, at the 27-foot depth, then the minimum casing depth setting would be 37 feet; or, for another example, if the static water level is at the 8-foot depth, then the minimum casing depth setting would be 25 feet.

For bedrock formation wells, the required casing depth setting is based on the depth to bedrock and on the type of bedrock. When the bedrock is encountered deep (greater than or equal to 30 feet for sandstone wells or greater than or equal to 40 feet for other types of bedrock), the upper-enlarged drillhole may be *mudded* to the top of the bedrock with a rotary rig or may be driven to the top of bedrock with a cable-tool or other percussion rig. The casing must be driven to a firm seat in the top of firm bedrock. An open drillhole can then be constructed into the bedrock.

When the bedrock is shallow (less than 30 feet for sandstone wells or less than 40 feet for other types of bedrock), an upper-enlarged drillhole must be constructed to at least the 30-foot depth for sandstone wells or to at least the 40-foot depth for other types of bedrock. Further, when limestone or dolomite bedrock is encountered at a depth less than 10 feet, then the upper-enlarged drillhole must be extended to at least the 60-foot depth. In either case the casing pipe must be set to the bottom of the upper-enlarged drillhole and must be sealed in place with neat cement grout.

For high capacity, school or wastewater treatment plant wells the minimum casing depth setting is 60 feet and the casing must always be sealed within an upper-enlarged drillhole with neat cement grout. However, when these wells are bedrock wells and the bedrock is encountered deeper than the 60-foot depth, then, of course, the upper-enlarged drillhole, casing pipe and required cement seal must extend to at least the top of the bedrock. For these wells the enlarged drillhole must be at least 3 inches larger in diameter than the outside diameter of the casing pipe or the casing couplings, if used.

SPECIAL WELL CASING PIPE DEPTH AREAS

For most areas of Wisconsin, the well casing pipe depth setting requirements described above are adequate to obtain uncontaminated groundwater and to prevent contamination of the aquifer. However, there are approximately 15 areas throughout Wisconsin where, for one reason or another, groundwater has been contaminated to significantly greater depths. In these areas, the standard required depths of casing do not extend deep enough to get below the *vertical zone of contamination* to prevent wells from becoming contaminated. As a result a greater depth of casing setting is required.

For example, in Door County in the northeastern part of the State, the entire county rests on a Silurian (Niagara) Dolomite *escarpment* (i.e. A high cliff plus it's gradual backslope). (Figure 25.) The dolomite is highly fractured and creviced and lies at a shallow depth below very thin soil. As a result it is very prone to groundwater contamination. In the early 1970's the entire county was designated as a special casing pipe depth area. It was subdivided into three areas. In one area a minimum casing depth setting of 170 feet is required. In another, 100 feet of casing is required. In a third area the casing depth setting is specified by the Department for each well on a case by case basis.

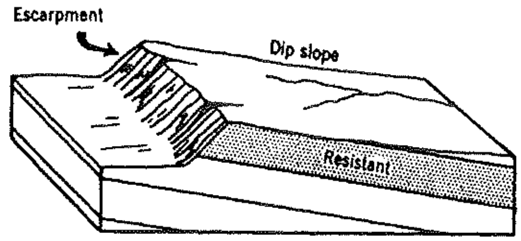


Figure 25. Topographic escarpment
(Trewartha, Robinson and Hammond, 1967)

WELL CASING PIPE

In Wisconsin the Private Well Code (NR 812) allows both steel and thermoplastic pipe for well casing. Thermoplastic pipe (usually PVC) is allowed only in sand and gravel formations, not for bedrock wells. Thermoplastic casing is also not allowed to be sealed in place with neat cement grout because of concern that the pipe may be damaged from the heat given off by the setting of the cement.

The Code has very stringent requirements for the types of casing pipe that may be used and for the minimum wall thickness of the pipe. The material specifications are based on the American Society of Testing Materials (ASTM) and the American Petroleum Institute (API) specifications. For standard 6-inch diameter steel pipe, the wall thickness must be at least 0.280 inches. The Department spends much time enforcing the requirements for the type of pipe material used and for proper pipe markings.

WELL GROUTING METHODS

The Private Well Code requires well casings to be grouted within an upper-enlarged drillhole whenever they are high capacity, school or wastewater treatment plant wells or whenever bedrock is encountered above the 40-foot depth (above the 30-foot depth for sandstone); OR, whenever the driller extends the upper-enlarged drillhole and casing pipe more than 5 feet into a bedrock formation encountered deeper than 40 feet (deeper than 30 feet for sandstone). Neat cement grout is a mixture of cement and water in the ratio of one 94-pound bag of cement with 5 to 6 gallons of water. (No aggregate is added.) The grout must be allowed to set for at least 12 hours after it is placed to prevent the grout from being damaged during subsequent drilling. There are several methods that have been approved for neat cement grouting of wells in Wisconsin. The three most commonly used are as follows:

Conductor Pipe-Pumped Method

The cement grout is placed into a hopper or funnel arrangement connected to a conductor (tremie) pipe that has been lowered to the bottom of the annular space between the casing and the drillhole. The grout is pumped down through the conductor pipe and fills the annular space from the bottom up. The end of the conductor pipe must be kept submerged in the grout throughout the process to prevent dilution of the grout from any water in the hole and to prevent gaps in the seal. (Refer to Figure 26.)

Conductor (tremie) pipe — pumped method

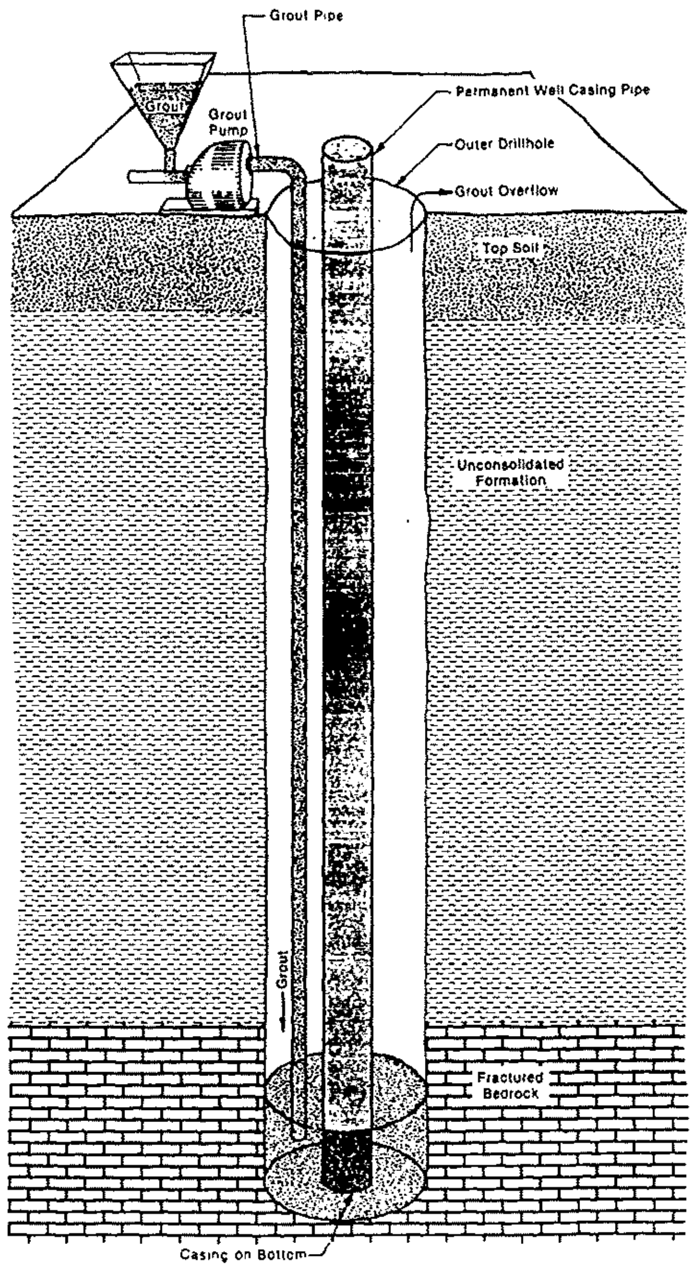


Figure 26. Conductor pipe-pumped method of cement grouting

Grout Shoe-Pumped Method

A *grout shoe* is installed on the bottom of the casing pipe. The grout shoe has a check valve incorporated into it. A conductor pipe is connected into the grout shoe and is extended up to the ground surface through the center of the casing. The casing is suspended several feet above the bottom of the enlarged drillhole. The grout is pumped down through the conductor pipe and forced up the annular space to the ground surface. After the grout flows out the top of the annular space, the conductor pipe is removed and the casing is set to the bottom of the enlarged drillhole. The check valve in the grout shoe prevents the grout from flowing up into the casing. After the grout has set for at least 12 hours, the grout shoe is drilled out the bottom of the casing and the lower drillhole is constructed. (Refer to Figure 27.)

Bradenhead Method

After completion of the upper-enlarged drillhole, the hole is filled with water or drilling mud. The casing is set within this drillhole and suspended several feet above the bottom of the hole. A conductor (tremie) pipe is then set inside the casing to the bottom. The top of the conductor pipe is extended watertight through a special well cap (bradenhead) that seals the top of the casing. The grout is pumped down through the conductor pipe and is forced up the annular space to the ground surface. The grout can only flow up the annular space between the outside of the casing and the inside of the enlarged drillhole. It cannot flow up inside the casing because the casing is filled with water and water is essentially incompressible. Immediately following completion of the grouting, the casing is set to the bottom of the drillhole and the grout is allowed to set. (Refer to Figure 28.)

HYDROFRACTURING

Hydrofracturing is a relatively new technique used for well development. It is typically used in crystalline bedrock type aquifers such as granite to try to increase the yield of water from a well. It is also sometimes used in sedimentary bedrock aquifers like sandstone and limestone, but much less frequently. This technique can greatly increase the yield of crystalline bedrock wells that originally produced very low yields. It not only increases the size of the cracks and crevices in the aquifer, but may also cause these fractures to be cleaned out and to become interconnected, thus allowing greater quantities of water to flow towards the well. (Figure 29.)

This technique involves the use of an cylindrical inflatable packer. The packer is inserted into the well to a specified depth in the open bedrock drillhole. The packer is then inflated with nitrogen gas to plug off the inside of the drillhole. A small diameter pipe extends down through the middle of the packer. (Figure 30.) Water under very high pressure—sometimes as high as 5,000 psi—is injected through the pipe into the open bedrock drillhole. This opens up, cleans out and creates fractures within the formation surrounding the well. Sometimes small amounts of sand or other inert material are injected along with the water to hold the cracks and crevices open after the pressure has been released. This new technique has had great success in Wisconsin and in some of the Rocky Mountain states where low producing crystalline bedrocks are the only available aquifers.

Grout (float) shoe — pumped method

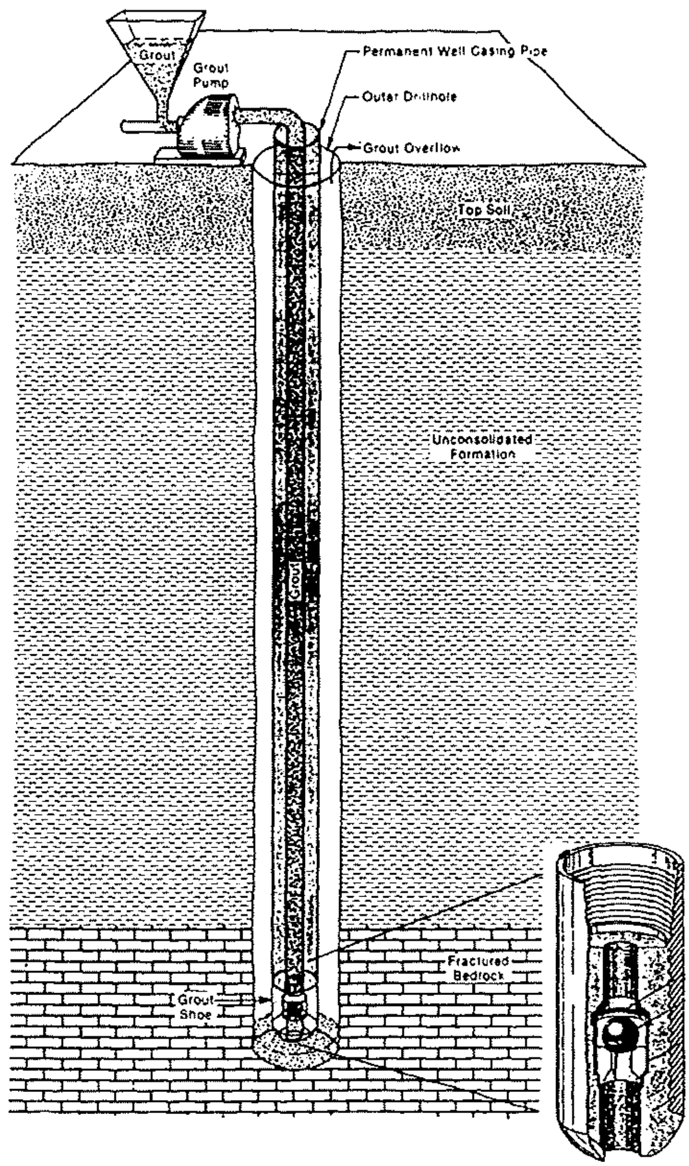


Figure 27. Grout shoe-pumped method of cement grouting

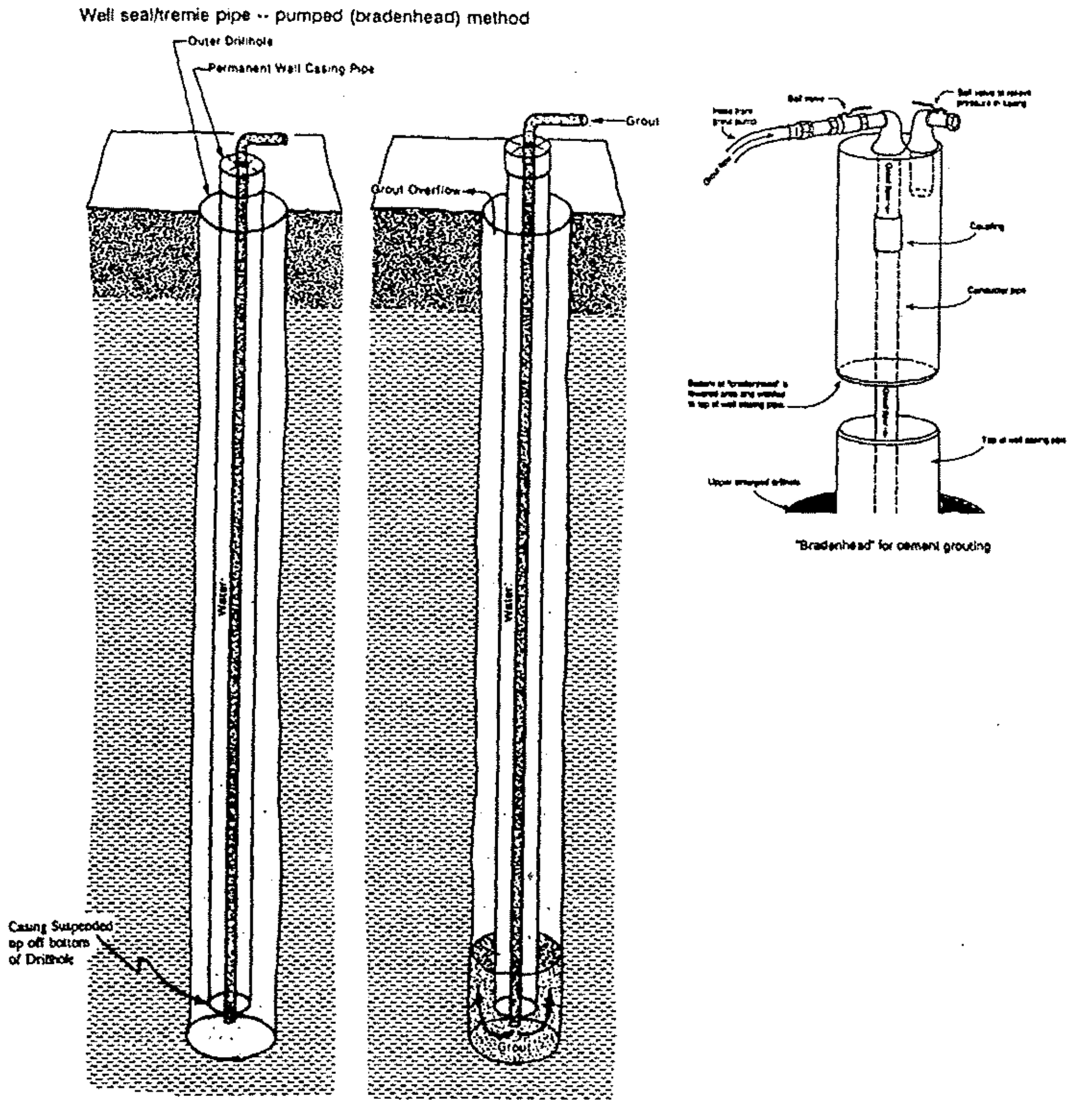


Figure 28. Bradenhead method of cement grouting

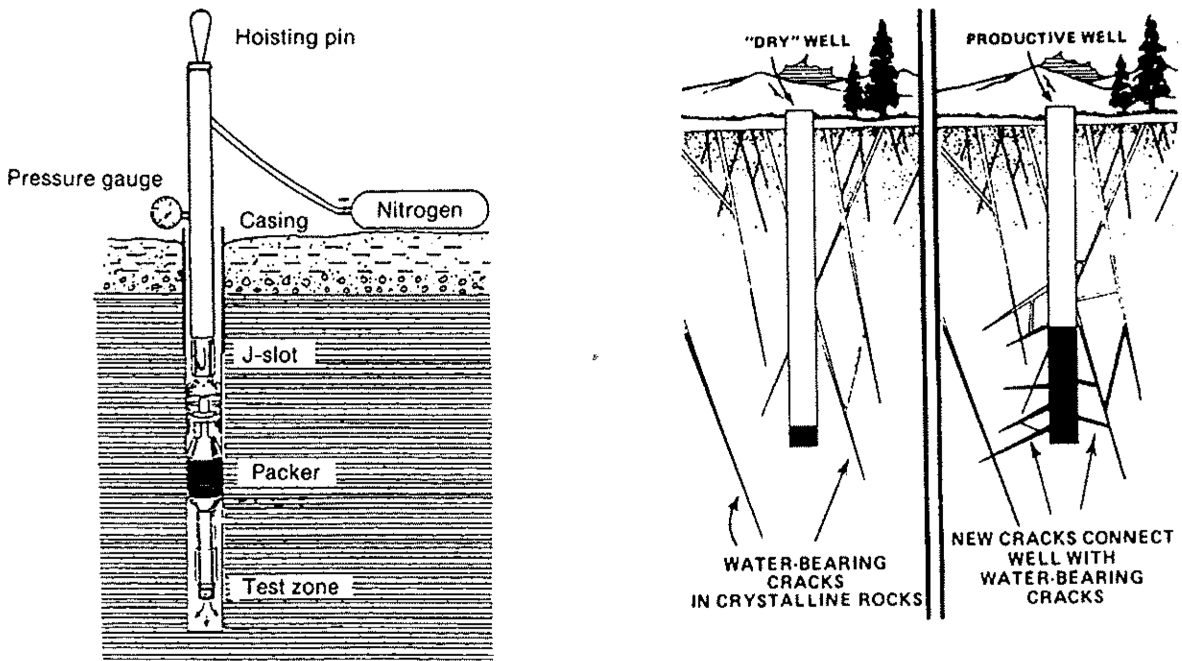


Figure 29. Hydrofracturing mechanism and results
(Smith, 1989; Geologic Resources
Investigations and Development)

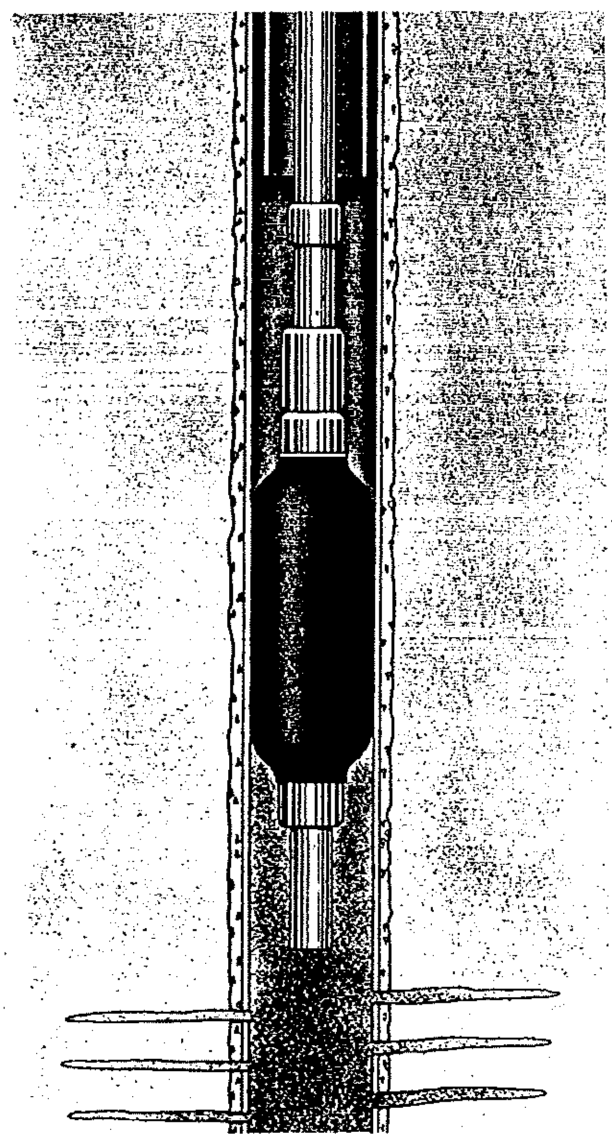


Figure 30. Inflatable packer.
(Tam International)

SUMMARY

Proper well location and construction methods have not only been very important in providing safe drinking water and protecting the aquifers of Wisconsin, but also have been a major contributing factor over the last 50 to 100 years in reducing the incidence of water-borne diseases. For example, in 1910 the State Board of Health reported an incidence of waterborne typhoid fever at a rate of 105 cases per 100,000 population. In 1936 the State Private Well Code went into effect. The enforcement of the well construction standards of this code and its later editions has, according the EPA, "...produced ... one of the greatest concentrations of properly constructed and protected water wells in the country." By 1970, the number of cases of waterborne typhoid fever in Wisconsin were zero.

Favorable results of proper well construction in Wisconsin were also demonstrated in a 1993 survey sponsored by the Center For Disease Control. The survey was funded by money allocated by the federal government to study the effects of the 1993 floods on the quality of groundwater. Wells were sampled at 10 mile intervals throughout the State. A total of about 700 wells were sampled. Of the five states in the upper midwest that participated in the survey, Wisconsin had the highest percentage of wells that produced bacteriologically safe water.

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